Selecting the Design Entering Water Temperature for Vertical Geothermal Heat Pumps in Cooling-Dominated Applications*

By

J. A. Shonder
Oak Ridge National Laboratory

J. Thornton
Thermal Energy Systems Specialists

P. J. Hughes
Oak Ridge Nationa Laboratory

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SELECTING THE DESIGN ENTERING WATER TEMPERATURE FOR VERTICAL GEOTHERMAL HEAT PUMPS IN COOLING-DOMINATED APPLICATIONS

John A. Shonder, Oak Ridge National Laboratory
Jeff Thornton, Thermal Energy System Specialists
Patrick Hughes, Oak Ridge National Laboratory

Abstract

At a military base in the Southeastern United States, an energy services company (ESCO) has proposed to retrofit more than 1,000 family residences with geothermal heat pumps as part of an energy savings performance contract (ESPC). Each residence is to have one heat pump with its own ground heat exchanger consisting of two or more vertical bores. A design firm hired by the ESCO sized the heat pumps to meet peak cooling loads, and sized the borefields to limit the maximum entering water temperature (EWT) to the heat pumps to 95°F (35°C). Because there is some disagreement in the geothermal heat pump industry over the peak temperature to be used for design (some designers and design manuals recommend temperatures as low as 85°F [29°C], while equipment manufacturers and others specify temperatures of 100°F [38°C] or higher) the authors were requested to examine the designs in detail to determine whether the 95°F (35°C) limit was adequate to ensure occupant comfort, efficient operation, and low capital and operating costs. It was found that three of the designer's assumptions made the borefield designs more conservative (i.e., longer) than the 95°F (35°C) limit would indicate. In fact, the analysis indicates that with more realistic assumptions about system operation, the maximum entering water temperature at the modeled residence will be about 89°F (32°C). Given the implications of a borefield that is shorter than required, it is likely that other designers are using similarly conservative assumptions to size vertical borefields for geothermal heat pumps. This implies that unless all of the design assumptions are examined, blanket recommendations to limit the entering water temperature to a specific value (such as 90°F [32°C]) may result in borefields that are significantly oversized.

1. Introduction

A primary objective in designing a space conditioning system for a given application is to size equipment to meet the expected heating and cooling loads. For equipment that exchanges heat with ambient air (air-cooled chillers and air source heat pumps for example), capacity and COP depend primarily on ambient conditions; equipment of this kind is sized according to the design space conditioning load, which depends on the ambient conditions of temperature and humidity that define the design condition. In the case of a geothermal heat pump (GHP) system, however, the design process is complicated by the storage of heat in the soil formation surrounding the ground heat exchanger. Since the performance of the ground heat exchanger at any given time depends on the quantity of heat that has been absorbed and rejected to the soil formation throughout the entire length of time since it was first installed, the proper design of a vertical ground heat exchanger generally requires information about heating and cooling loads throughout a typical year, as well as the loads on peak heating and cooling days.

A number of computer programs have been developed to assist in the design of vertical ground heat exchangers. Although each program uses a slightly different algorithm, all function in basically the same way: given the characteristics of the soil (thermal conductivity, thermal diffusivity, and undisturbed temperature), the borefield (number of boreholes, pattern, bore diameter, bore-to-bore spacing, and the thermal properties of the grout), the u-tube (diameter, material, and assumed spacing between the two legs), the heat transfer fluid (composition and flow rate), the heat pump (COP/EER and capacity as a function of entering water temperature), and the space conditioning loads (peak or peak block loads at design condition, and annual or monthly total loads), the programs determine the heat exchanger length required to limit the entering water temperature (EWT) to some prescribed value over the design period, typically from one to ten years. In applications where heating loads predominate, the heat exchanger is designed so that the EWT remains above a specified minimum temperature (usually in the range of 30°F – 45°F [-1°C – 7°C]). In cooling dominated applications, the heat exchanger is designed so that the EWT remains below a specified maximum temperature. The programs generally size the heat exchanger for both heating and cooling, and select the longer bore length.

Presently there is some disagreement in the GHP industry as to the maximum entering water temperature that should be used for the design of cooling-dominated systems. An earlier ASHRAE design manual (Bose et al., 1985) recommends design temperatures in the range of 85°F to 100°F (29°C to 38°C). A more recent ASHRAE publication (Kavanaugh and Rafferty, 1997) makes no specific recommendation, but implies that the maximum temperature should be limited to between 85 and 90°F (29°C and 32°C). Nevertheless, a number of other system designers recommend maximum entering water temperatures in the range of 95°F – 100°F (35°C – 38°C). Equipment manufacturers publish performance data for entering water temperatures as high as 110°F (43°C) (ClimateMaster, 2000).

The design maximum EWT has a large effect on the design length of a vertical ground heat exchangers. While the magnitude of this effect depends on the particular application, a study performed for the evaluation of the GHP retrofit at Fort Polk, LA (Hughes and Shonder, 1998) showed that the design heat exchanger length for a typical housing unit increased by 33% when the design maximum entering water temperature was decreased from 95°F (35°C) to 85°F (29°C). With vertical loop installation costs of at least $4 to $5 per bore foot ($13 to $16 per meter), a 33% increase in required bore length can have a significant impact on project economics.

Although a lower design EWT increases drilling costs, this can be partially offset by reduced operating costs. The increased length associated with a lower design EWT causes lower EWTs during cooling operation and warmer EWTs when heating, and may result in slightly more efficient operation throughout the year. Regardless of the design maximum EWT chosen, it is important to determine whether the system can actually satisfy the building design cooling load at the maximum EWT. Maximum EWT does not necessarily occur at cooling design conditions, but this assumption is considered prudent and is commonly made.

For a project that has not yet been constructed, a detailed simulation model such as the one developed for this paper can provide some useful insights into design issues. Those developing large GHP projects to improve existing facilities have the opportunity to acquire monitored interval data to calibrate detailed models such as the one described here, and explore design issues in greater detail.

2. Project Background

As part of an energy savings performance contract, vertical-loop geothermal heat pumps are to be installed in more than 1,000 family residences at a military base in a coastal location in the Southeastern U.S. The residences, ranging in size from 978 to 1880 square feet (91 m^2 to 175 m^2), are currently served by air source heat pumps or central air/gas furnace combinations. A single heat pump will be installed in each residence, and each heat pump will be connected to its own ground heat exchanger consisting of two or more vertical bores. The majority of the residences will receive 1.5 ton (5.3 kW) or 2.0 ton (7.0 ton) units, and a small number of 2.5 ton (8.8 kW) and 3.0 ton (10.6 kW) units are to be installed in larger residences. The heat pumps include desuperheaters to supplement hot water tank heating elements.

The designs of the vertical heat exchangers for each residence were developed by a design firm (hereafter referred to as 'the designer') subcontracted to an energy services company. The design process began with collection of detailed as-built construction drawings for the 22 unique floor plans represented in the housing area of the military base. Construction details (floor areas, wall thicknesses, window areas, material composition, etc.) were used to develop load models in the PowerDOE building energy analysis software (Hirsch et al., 1998). Hourly heating and cooling loads for each residence were then estimated by running the PowerDOE models with the correct building orientation, and standard assumptions for lighting and appliance loads, hot water loads, and occupancy schedules.

Because long-term weather data is not available for the actual site, the typical meteorological year for a nearby city was used to drive the simulations. This city is approximately 50 miles (80 km) away from the site in question, with both cities located about 10 miles (16 km) from the Atlantic coast.

The designer used the hourly heating and cooling loads for each residence to develop inputs for a popular commercially-available borefield sizing program. The program inputs for soil thermal conductivity and deep earth temperature were based on in-situ field tests carried out at various locations on the site. The measured thermal conductivities were surprisingly low for a coastal location, ranging from 0.9 to 1.0 BTU/hr-ft-°F (1.6 to 1.7 W/m-K). Undisturbed soil temperature was measured at approximately 64°F (18°C) in all locations. The boreholes were assumed to be 4.5 inches (11.4 cm) in diameter, with 20 ft. (6 m) center-to-center spacing, and backfilled with soil cuttings. The u-tube heat exchanger was nominal 1-inch (2.54 cm) diameter SDR-11 high density polyethylene.

Given all of these inputs, the designer exercised the borefield sizing software to determine heat exchanger lengths for each residence with maximum EWTs of 85°F (29°C), 90°F (32°C) and 95°F (35°C). The ESCO examined these numbers and proposed to install the 95°F (35°C) design lengths for each residence; on average these are about 25% shorter than the 85°F (29°C) design lengths.

It is important to note that in sizing the borefield for each residence, the designer included three different margins of safety in the design. First, their loads model did not include the effect of the desuperheaters. A ground loop designed to reach a peak EWT of 95°F (35°C) will likely reach a slightly lower temperature in an actual residence using a desuperheater, because some of the heat is rejected to the hot water tank rather than to the ground.

The second safety margin was to derate the heat pumps by 5%. In the equipment model, the designer assumed that the heat pump required 5% more input power than the catalog data indicated, at all entering water temperatures. Since cooling capacity was assumed to be the same as the catalog data, this had the effect of reducing EER and increasing the heat of rejection. A ground loop designed for a peak EWT of 95°F (35°C) for a heat pump with 5% degradation will likely reach a lower EWT if the heat pump performs according to catalog specifications.

Finally, the designer used heating and cooling setpoints of 70°F (21°C) and 72°F (22°C) respectively. While the heating setpoint is realistic, the cooling setpoint is a temperature that some residents may find uncomfortably cool (depending on humidity). A ground loop designed for a peak EWT of 95°F (35°C) with a cooling setpoint temperature of 72°F (22°C) will likely reach a lower maximum EWT if the residents set the cooling setpoint to a higher temperature.

Despite the low measured thermal conductivity, according to personnel at the base, other tests have indicated the presence of significant groundwater flow, on the order of one foot per day. For this reason, the designer chose to size the borefields to limit the entering water temperature to the heat pump to the maximum value over a period of one year. At other sites with less groundwater flow, design periods of up to 10 years may be warranted.

3. Development of Independent Simulation Model

Because of the disagreement in the GHP industry over the correct maximum EWT to use for design, the authors were asked by officials at the base to develop an independent simulation model of one of the residences at the site. Accordingly, as-built construction plans were obtained for a 1,300 square foot (120 m^2) residence (designated as L3 in the analysis of the 22 unique floor plans). Using these plans, a model for the residence was created using the TRNSYS simulation software package (Klein et. al, 1996). The GHP model was also created in TRNSYS based on manufacturers' catalog data. A desuperheater model was also included. The ground loop model for the geothermal heat pump is the same one that has been used successfully to benchmark and compare the available ground loop sizing programs for residential and commercial applications (Thornton et al., 1997; Shonder et al., 1999; Shonder et al., 2000).

Initially, the heating and cooling loads from the TRNSYS model were about 25% higher than the loads predicted by the designer's PowerDOE model. Since the objective here was not to perform an independent load calculation, the parameter controlling the rate of outdoor air infiltration in the TRNSYS model was adjusted until the loads matched those of the PowerDOE model. The accuracy of the match is shown in Figures 1 and 2, which present the daily total heating and cooling loads for both the TRNSYS and the PowerDOE models, plotted against the average temperature for each day in the typical meteorological year.

Once the TRNSYS loads model was calibrated to the designer's model, the TRNSYS model was run a number of different times. First, the TRNSYS model was run with the three margins of safety (no desuperheater, 5% heat pump degradation, and a 72°F [22°C] cooling setpoint) to determine the design length that caused the maximum EWT to reach 95°F (35°C) for a one year design period. This corresponds to the base case. Next, the safety margins were eliminated one by one to determine their effect on maximum EWT. Finally, with no safety margins included, the model was run to determine the maximum EWT that would occur after a 20 year period.

For all runs, a soil thermal conductivity of 0.93 BTU/hr-ft-°F (1.6 W/m-K) was used, with a deep earth temperature of 64°F (18°C). The boreholes were assumed to be 4.5 inches (2.54 cm) in diameter, spaced 20 feet (6 meters) apart, and backfilled with soil cuttings that have the same properties as the soil. The u-tubes were nominal 1" (2.54 cm) SDR-11 high density polyethylene, with average spacing between the two pipes.

4. Results

With the three safety margins included, the TRNSYS simulation was run at a number of different bore lengths to determine the length that caused the maximum EWT to reach 95°F (35°C) during the one year design period. The length of each bore was found to be 258 feet (79 m); since there are two bores, this corresponds to 516 bore feet (157 m), or

258 bore feet per ton (22.4 m/kW). This figure may seem rather large in light of popular rules of thumb such as 175 bore feet per ton (15 m/kW), but it is due to the low conductivity of the soil measured at the site, as well as the lack of significant heating loads.

When the borefield sizing software used by the designer was run using outputs developed from the TRNSYS simulation, it recommended a bore length of 522 bore feet (159 m), or 261 bore feet per ton (22.6 m/kW). This is only about 2% more than the bore length results from the TRNSYS model. The fact that the sizing software recommends a slightly longer bore length than the TRNSYS model means that for this building and these loads, it includes a small built-in margin of safety, at least when compared to the TRNSYS simulation.

The TRNSYS base case then corresponds to two bores, each at 258 feet (78.6 m) deep. For typical meteorological conditions, this borefield causes the maximum EWT to reach 95°F (35°C) during the first year of operation. This simulation includes the three margins of safety used by the designer: 1) no desuperheaters; 2) 5% degradation of the heat pumps; and 3) 72°F cooling setpoint. The dashed line in Figure 3 is an EWT duration curve for the base case. The simulation indicates that the maximum EWT is met during a total of just 24 hours for the year.

As stated above, a ground loop designed to reach a peak EWT of 95°F (35°C) will reach a slightly lower temperature in an actual residence using a desuperheater, because some of the heat is rejected to the hot water tank rather than to the ground. The TRNSYS simulation bore this out. When the desuperheater model was included, maximum EWT for the one year design period dropped to 92.8°F (33.8°C). Thus, designing without reference to the desuperheaters results in a 2.2°F (1.2°C) margin of safety on maximum EWT.

The TRNSYS simulation also showed that a ground loop designed for a peak EWT of 95°F (35°C) for a heat pump with 5% degradation will reach a lower EWT if the heat pump performs according to catalog specifications. When the 5% performance degradation was removed from the simulation, the maximum EWT for the one year design period was only 94.6°F (34.8°C). For this case, including the 5% degradation factor results in a 0.4°F (0.2°C) margin of safety on maximum EWT.

Also as expected, the TRNSYS simulation showed that a ground loop designed for a peak EWT of 95°F (35°C) with a cooling setpoint temperature of 72°F (22°C) reaches a lower maximum EWT when the cooling setpoint is 75°F (24°C). When the cooling setpoint was set to 75°F (24°C), the maximum EWT for the one year design period reached just 90.9°F (32.7°C). For this residence, assuming a cooling setpoint of 72°F (22°C) results in a 4.1°F (2.3°C) margin of safety on maximum EWT.

Finally, all three margins of safety were removed from the simulation. In other words, the final run included the desuperheaters, used catalog heat pump performance, and used a 75°F (24°C) cooling setpoint. For this case, the maximum EWT for the one year design period was found to be 88.9°F (31.6°C). This indicates that the three conservative assumptions made by the designer result in a margin of safety of 6.1°F (3.4°C) on maximum entering water temperature for the one year design period. The solid line in Figure 3 is the duration curve for the case with all three safety margins. The maximum EWT of 88.9 °F (31.6°C) is reached during only 18 hours throughout the year.

The one feature of the design that was not conservative was the use of the one year design period. An ASHRAE design manual for ground source heat pumps (Kavanaugh and Rafferty, 1997) indicates that a one year design period is warranted for high rates of groundwater flow. However, the manual does not specify what flow rate is to be considered high. In order to predict what might happen in a location with low groundwater flow, the TRNSYS model was run for a twenty year period with all safety margins removed. Figure 4 presents the maximum entering water temperature for each year, for twenty years. The rise in maximum EWT over the twenty year period is about 6°F (3.3°C). Although tests have indicated the presence of significant groundwater flows at the site, this result shows that even in relatively dry soil, the EWT would not reach 95°F (35°C) even after 20 years of operation, at least given typical year heating and cooling loads.

A reason sometimes given for specifying lower maximum EWTs is increased operating efficiency: since the heat pump EER increases as entering water temperature decreases, specifying a lower peak EWT should cause the system to operate more efficiently, thereby reducing operating costs. Examination of Figure 3 suggests that any savings due to this effect should be relatively small, since the majority of operating hours are well below the peak.

Lowering the maximum design EWT will also affect pumping power. On the one hand, with longer bore lengths, more power will be required to pump the water around the loop. On the other hand, however, the lower EWTs will increase the capacity of the heat pump slightly, and so the run time of the system may decrease. This could offset any increase in pumping power due to longer bore lengths.

With the detailed TRNSYS simulation, these effects can be quantified. To develop the data in Table 1, the baseline model (which includes all three conservative assumptions, and sizes the borefield to meet a peak EWT of 95°F (35°C)) was re-run to meet peak EWTs of 90°F (32°C) and 85°F (29°C). As shown in the Table, reducing the design EWT does reduce annual energy use; however, the effect is quite small. Pumping power was virtually unchanged for the three cases. Using nominal drilling costs of $5.00 per foot, and electrical costs of 6 cents per kilowatt-hour, decreasing the design EWT from 95°F (35°C) to 90°F (32°C) reduces annual electrical costs by $6.00, but increases drilling costs by $310.00. For this application, there is no life-cycle cost advantage to reducing peak EWT.

It must be stressed that this result is dependent on the assumed drilling costs and electricity rates, the soil properties, and the heating and cooling loads for this application.

For example, in an area with very high electrical costs, on a project with very low drilling costs, there ~~may~~ could conceivably be be an advantage to reducing peak EWT.

5. Conclusions

The results of this study show that the designer employed a number of experience-based margins of safety to ensure that the designs are conservative. Using an independent TRNSYS simulation of a typical residence at the site, it has been shown that with a design maximum EWT of 95°F (35°C), the use of three different margins of safety brings the effective maximum EWT down to 88.9°F (31.6°C) for a one year design period. The fact that the designer does not consider the effect of the desuperheaters when designing the borefield implies a safety margin of about 2.2°F (1.2°C) on maximum EWT; the assumption of a cooling setpoint of 72°F (22°C) produces a safety margin of 4.1°F (2.2°C) on maximum EWT. The 5% heat pump degradation produces a safety margin of 0.4°F (0.2°C).

Given the consequences of underdesigning the borefield, it is likely that other designers are using similarly conservative assumptions. The use of margins of safety such as these makes it difficult to prescribe hard and fast rules for maximum entering water temperatures for borefield heat exchanger design. For example, were the bores for this residence designed to limit EWT to 90°F (32°C) rather than 95°F (35°C), the three safety margins would cause the borefield to be designed for 83.9°F (28.9°C), resulting in much higher borefield costs. The energy savings that result from lower design EWT do not make up for the increased drilling cost, at least in this application. Before making any recommendations as to design EWT, designers and consultants should consider all of the assumptions that were made in the design. Ignoring these assumptions may result in bores that are much longer than actually required, increasing the cost of the system with only very small gains in efficiency.

Table 1: Effect of design maximum entering water temperature on borefield size, borefield cost, annual energy use by the geothermal heat pump and annual energy costs.

Design EWT	Bore length, ft/ton (m/kW)	Annual energy use, kWh	Approximate borefield cost	Annual energy cost
95°F (35°C)	258 (22)	4670	$2580	$280
90°F (32°C)	289 (25)	4569	$2890	$274
85°F (29°C)	332 (29)	4468	$3320	$268

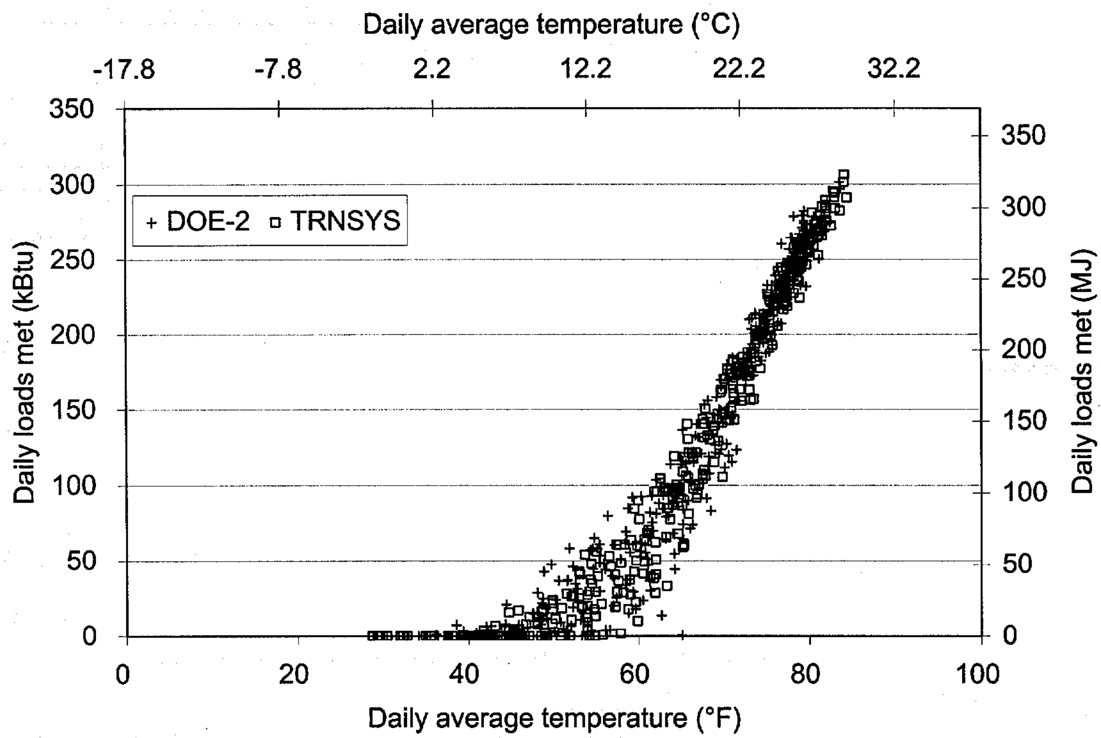

Figure 1: Daily cooling load met vs. daily average temperature, TRNSYS and DOE-2.

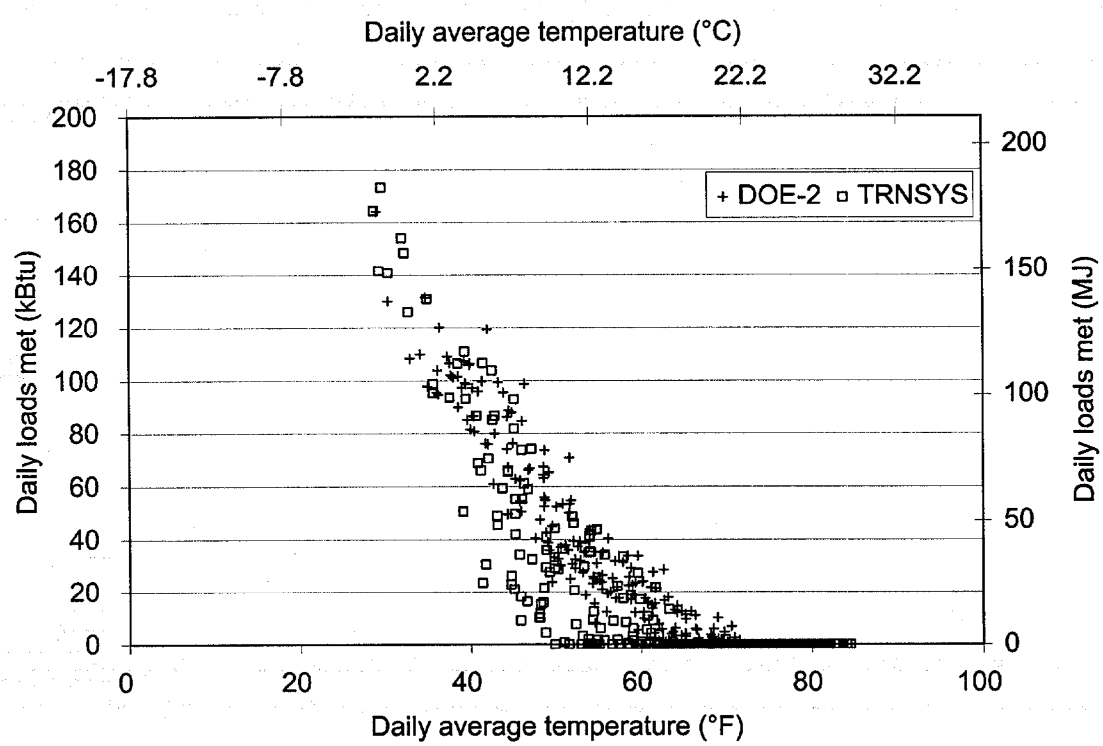

Figure 2: Daily heating load met vs. daily average temperature, TRNSYS and DOE-2.

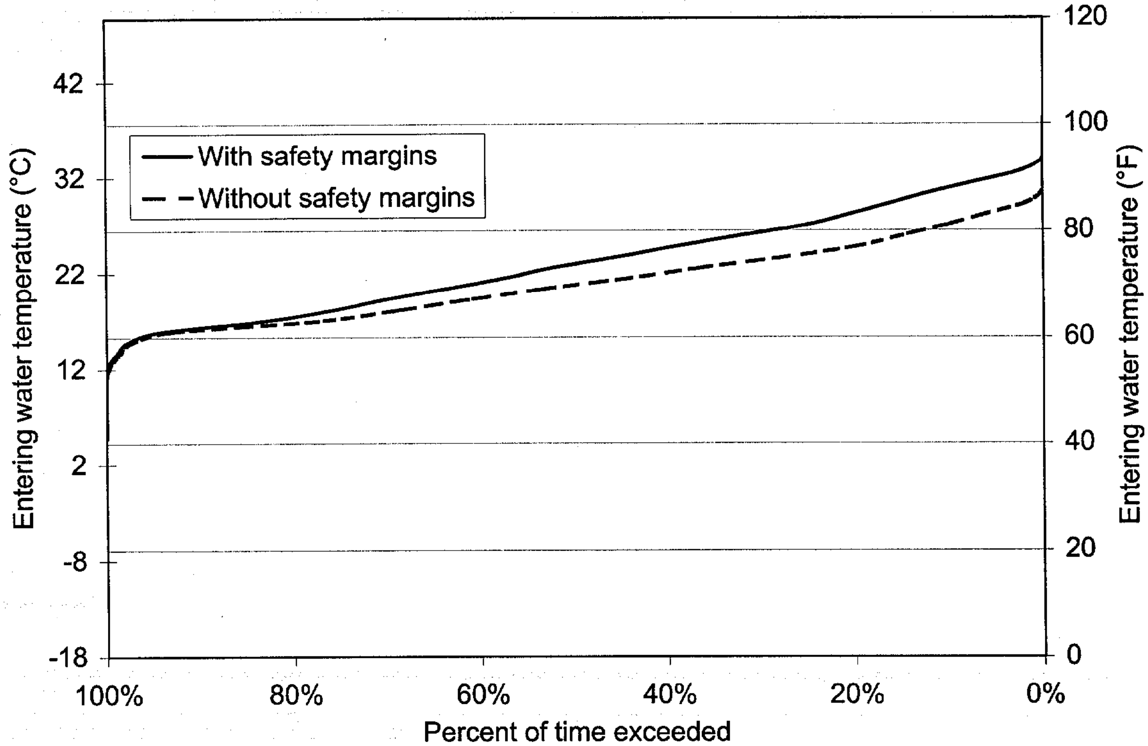

Figure 3: Entering water temperature duration curve, with and without safety margins.

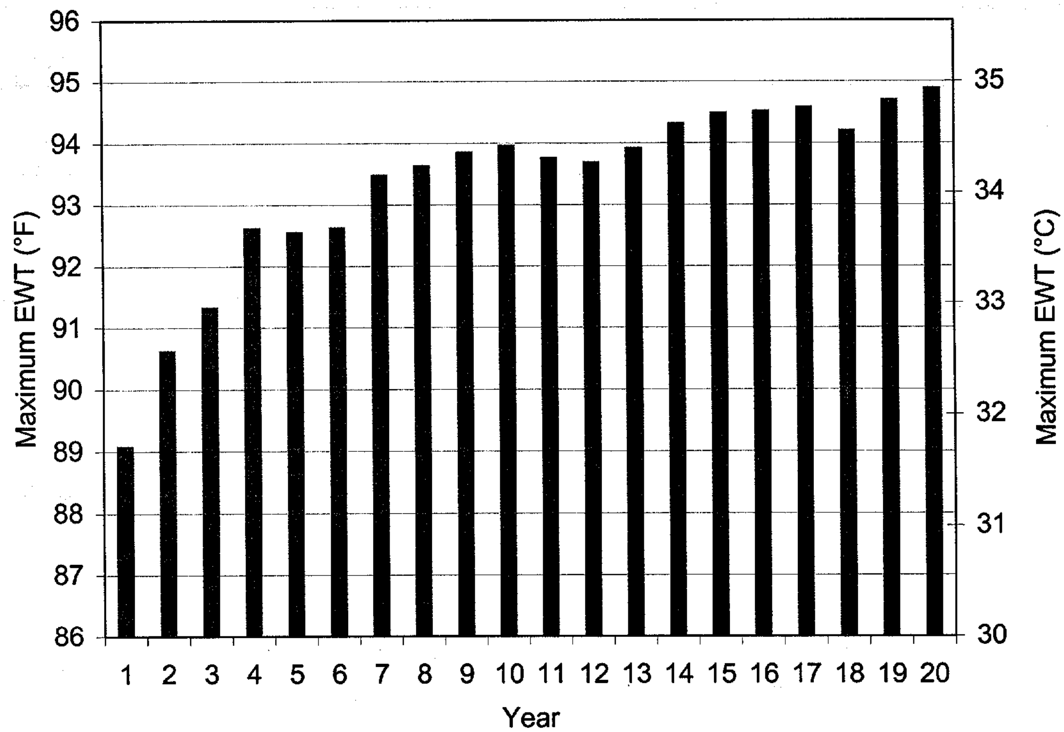

Figure 4: Annual maximum entering water temperature to heat pump, years 1 - 20 for TRNSYS simulation with no safety margins.

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